Sterile Neutrinos at High Δm^2?

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Outline

- Motivations

- Current experimental constraints on two possible sterile neutrino models

- Which future experiments can find sterile neutrinos at high Δm^2?

Theoretical Motivations

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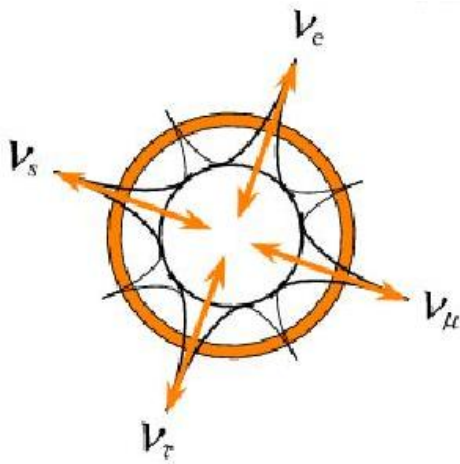
- Grand Unified Theories
  Mohapatra, `hep-ph/0107264`, McKeller et al., `hep-ph/0106121`,...

- SuperSymmetry
  Dvali et al., `hep-ph/9810257`, Arkhani-Amed et al., `hep-ph/0006312`,...

- Extra-Dimensions
  Ioannisian et al., PRD**63** 073002, Ma et al., `hep-ph/0006340`,...

Experimental Motivations

- There are three experimental hints pointing toward neutrino oscillations:
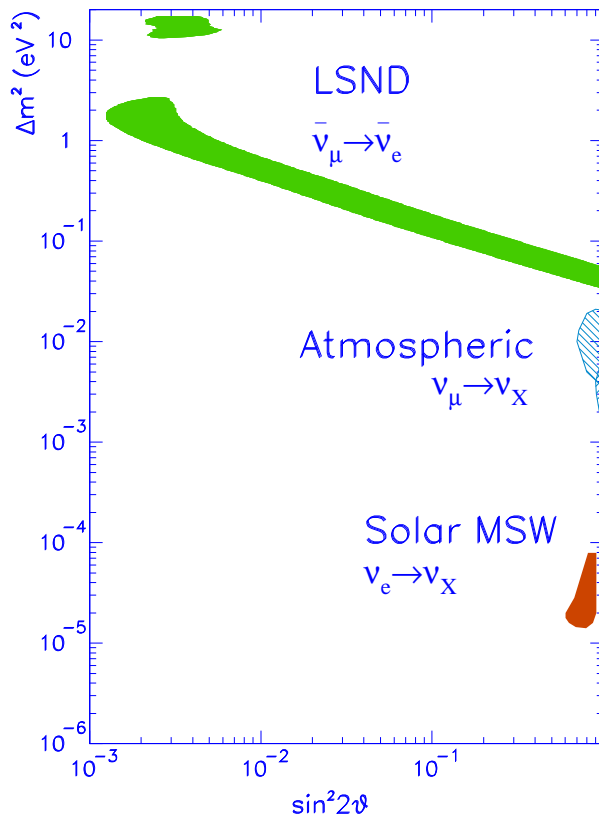
- Two-neutrino oscillation approximation:

$$\left(\begin{array}{c} \nu_\alpha \\ \nu_\beta \end{array} \right) = \left(\begin{array}{cc} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{array} \right) \left(\begin{array}{c} \nu_1 \\ \nu_2 \end{array} \right), \; \Delta m^2 = m_2^2 - m_1^2$$
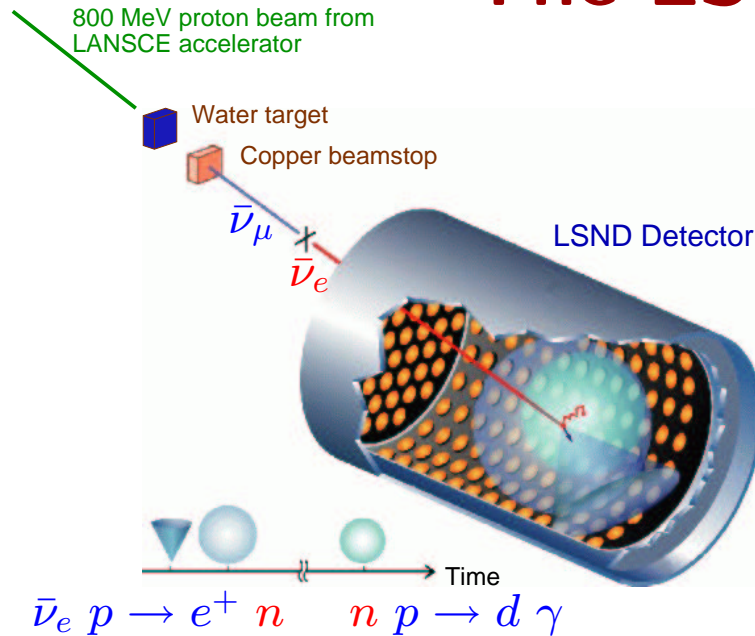
- Oscillation probabilities:

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta_{\alpha\beta} \sin^2(1.27\Delta m^2 L/E), \; \alpha \neq \beta$$

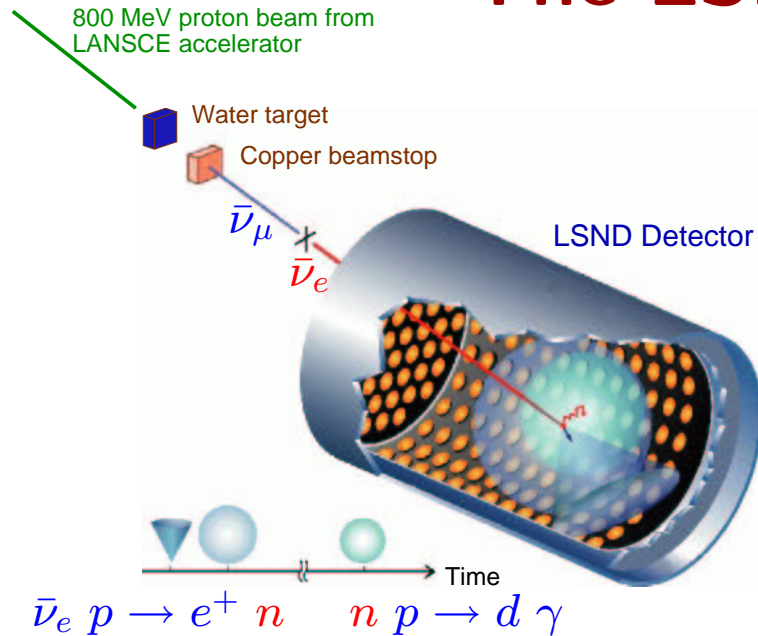$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2(1.27\Delta m^2 L/E)$$

- $\Delta m^2_{sol} + \Delta m^2_{atm} \neq \Delta m^2_{LSND} \Rightarrow$ need more than three massive neutrinos?

The LSND Result ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)

800 MeV proton beam from LANSCE accelerator

Water target

Copper beamstop

$\bar{\nu}_\mu$

$\bar{\nu}_e$

LSND Detector

Time

$\bar{\nu}_e \, p \rightarrow e^+ \, n$ $n \, p \rightarrow d \, \gamma$

- $\bar{\nu}_\mu$ source from: $\pi^+ \rightarrow \mu^+ \, \nu_\mu$
  $$\hookrightarrow e^+ \, \nu_e \, \bar{\nu}_\mu$$

- $E_\nu = $ 20-53 MeV, $L_\nu = $ 25-35 m

- Liquid scintillator detects both Cherenkov and scintillation light
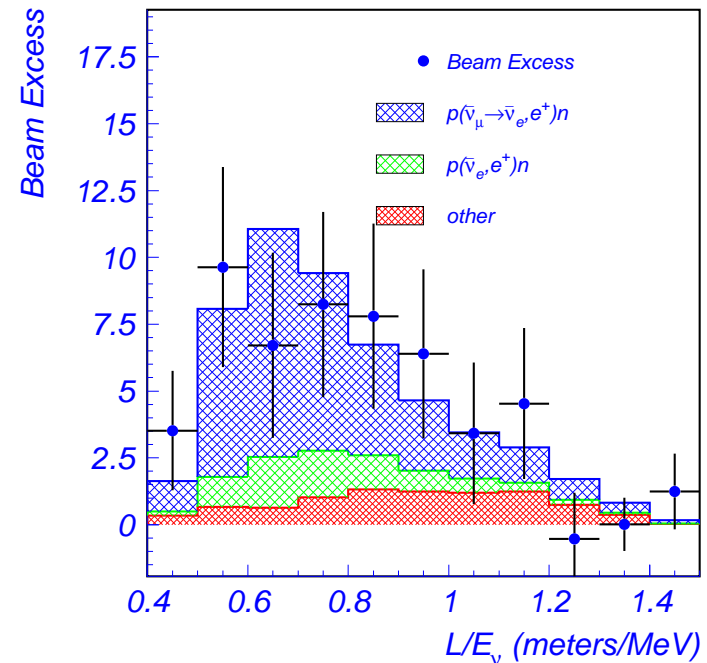
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- $3.8\sigma \ \bar{\nu}_e$ excess:
  $\langle P(\bar{\nu}_\mu \to \bar{\nu}_e) \rangle = (0.264 \pm 0.045 \pm 0.067)\%$

- L_ν/E_ν distribution of the excess (backgrounds in green,red, fit to oscillation hypothesis in blue):

Beam Excess

- Beam Excess
- $p(\bar{\nu}_\mu \to \bar{\nu}_e, e^+)n$
- $p(\bar{\nu}_e, e^+)n$
- other

L/E_ν (meters/MeV)

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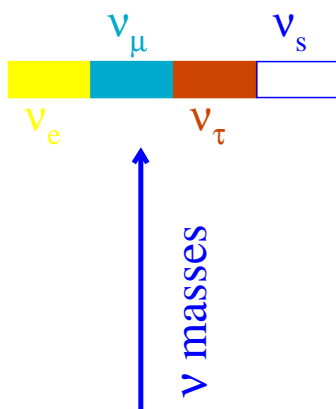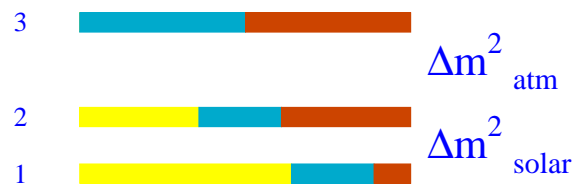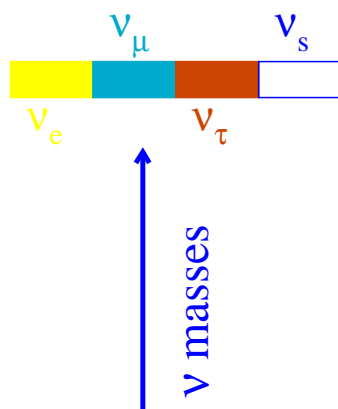

Reactor $\bar{\nu}_e \to \bar{\nu}_e$

Solar $\nu_e \to \nu_e, \ \nu_e \to \nu_{\mu,\tau}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric $\nu_\mu \to \nu_\mu, \ \nu_\mu \to \nu_e, \ \nu_\mu \to \nu_\tau$

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Atmospheric $\nu_\mu \to \nu_\mu, \ \nu_\mu \to \nu_e, \ \nu_\mu \to \nu_\tau$

$$|U| = \begin{pmatrix} 0.70 - 0.87 & 0.50 - 0.69 & < 0.16 \\ 0.20 - 0.61 & 0.34 - 0.73 & 0.60 - 0.80 \\ 0.21 - 0.63 & 0.36 - 0.74 & 0.58 - 0.80 \end{pmatrix}$$
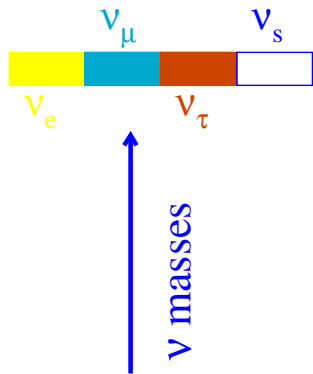
(Bandyopadhyay *et al.*, PLB 559, 2003)
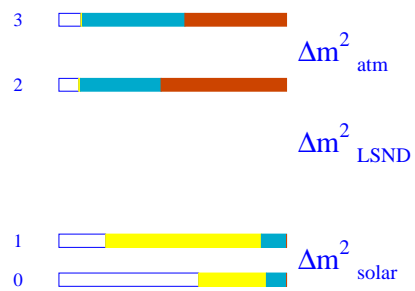
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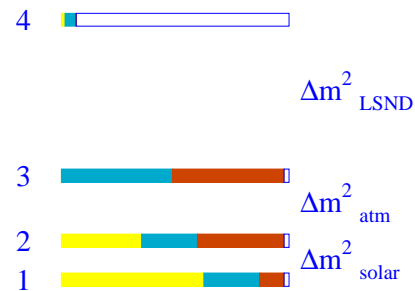
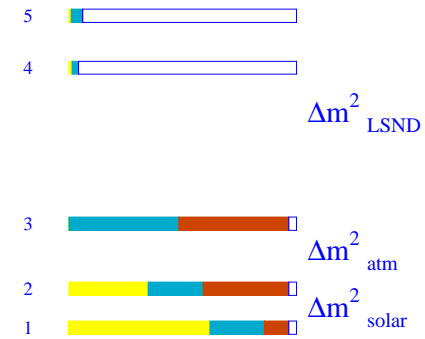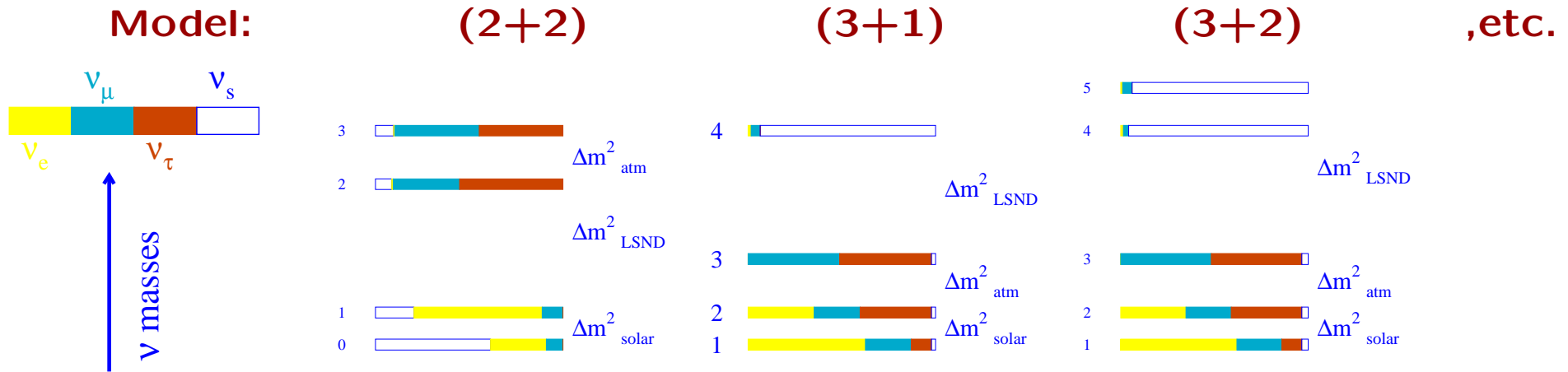- CPT-conserving models, with sterile neutrinos:
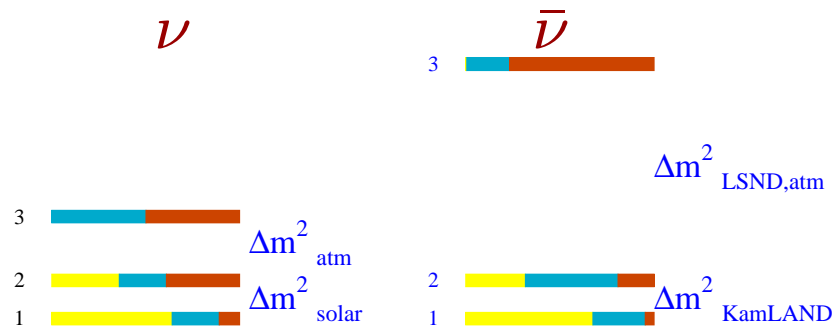
Model: **(2+2)** **(3+1)** **(3+2)** ,etc.

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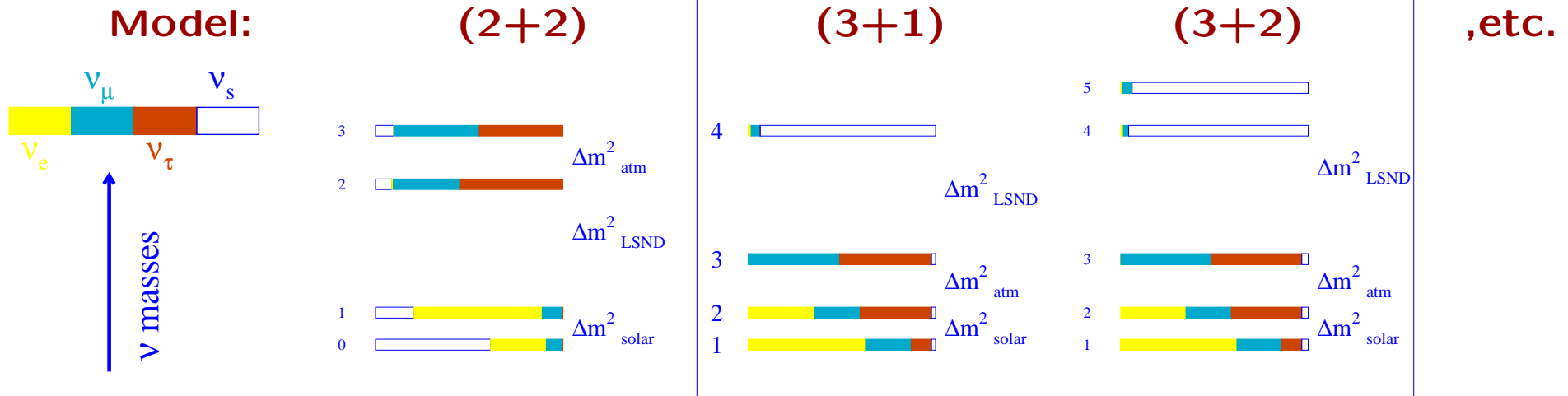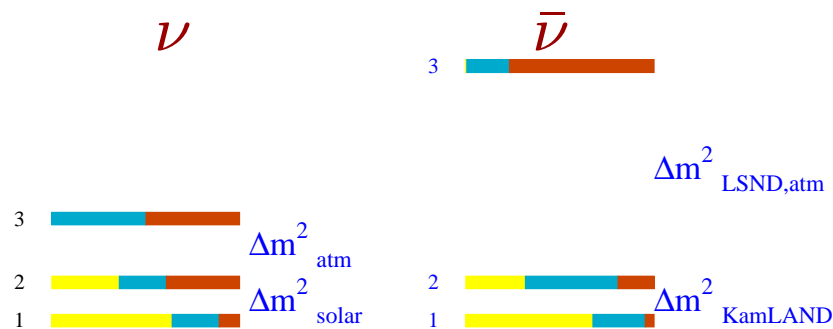- CPT-conserving models, with sterile neutrinos:

- CPT-violating models, with no sterile neutrinos:
  (G. Barenboim, "Is nothing sacred? CPT violation in neutrino physics", this session)

If LSND is due to oscillations...

- CPT-conserving models, with sterile neutrinos:

Model: (2+2) (3+1) (3+2) ,etc.

ν_μ ν_s ν_e ν_τ

ν masses

(2+2): levels 3, 2 with Δm^2_{atm}, Δm^2_{LSND}; levels 1, 0 with Δm^2_{solar}

(3+1): levels 4, 3, 2, 1 with Δm^2_{LSND}, Δm^2_{atm}, Δm^2_{solar}

(3+2): levels 5, 4, 3, 2, 1 with Δm^2_{LSND}, Δm^2_{atm}, Δm^2_{solar}

- CPT-violating models, with no sterile neutrinos:
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ν $\bar{\nu}$

(ν): levels 3, 2, 1 with Δm^2_{atm}, Δm^2_{solar}

($\bar{\nu}$): level 3 with $\Delta m^2_{LSND,atm}$; levels 2, 1 with $\Delta m^2_{KamLAND}$

I will discuss experimental constraints on these models

(work in collaboration with J. Conrad, M. Shaevitz)

Combined analysis of SBL experiments

● Short-baseline experiments on

1. ν_μ disappearance (CCFR84, CDHS)
2. $\bar{\nu}_e$ disappearance (Bugey, CHOOZ)
3. $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance (LSND, KARMEN)

probe the same Δm^2 range and the same matrix elements:

$$
\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_{s'} \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & U_{\mu 5} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & U_{\tau 5} & \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & U_{s5} & \\ U_{s'1} & U_{s'2} & U_{s'3} & U_{s'4} & U_{s'5} & \\ & & \cdots & & & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \vdots \end{pmatrix}
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U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} & U_{\tau5} & \\
U_{s1} & U_{s2} & U_{s3} & U_{s4} & U_{s5} & \\
U_{s'1} & U_{s'2} & U_{s'3} & U_{s'4} & U_{s'5} & \\
& & \cdots & & &
\end{pmatrix}
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- Only LSND demands $U_{e4}U_{\mu4} \neq 0$, or $U_{e5}U_{\mu5} \neq 0$, etc.

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$$

- Only LSND demands $U_{e4}U_{\mu4} \neq 0$, or $U_{e5}U_{\mu5} \neq 0$, etc.

- Is LSND consistent with the upper limits on active-sterile mixing at high Δm^2 derived by the null short-baseline experiments (NSBL)?

- NSBL = Bugey + CHOOZ + CCFR84 + CDHS + KARMEN

(3+1) models and SBL experiments
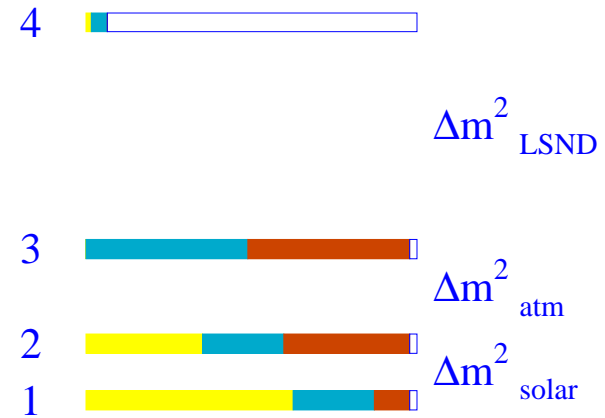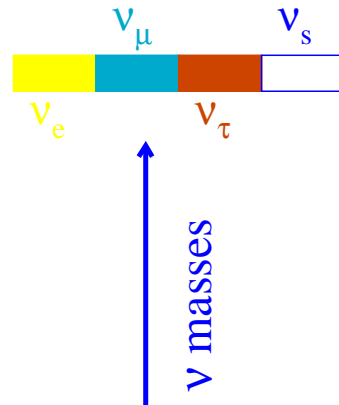
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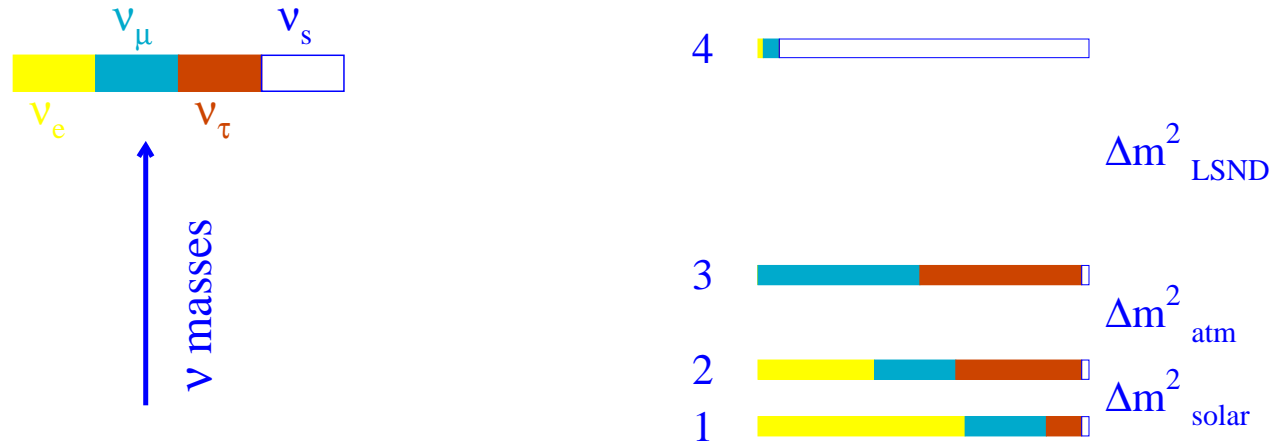
- Three parameters probed: Δm^2_{41}, U_{e4}, $U_{\mu4}$ (SBL only: can assume $\Delta m^2_{21} = \Delta m^2_{32} = 0$)

- Oscillation probability:

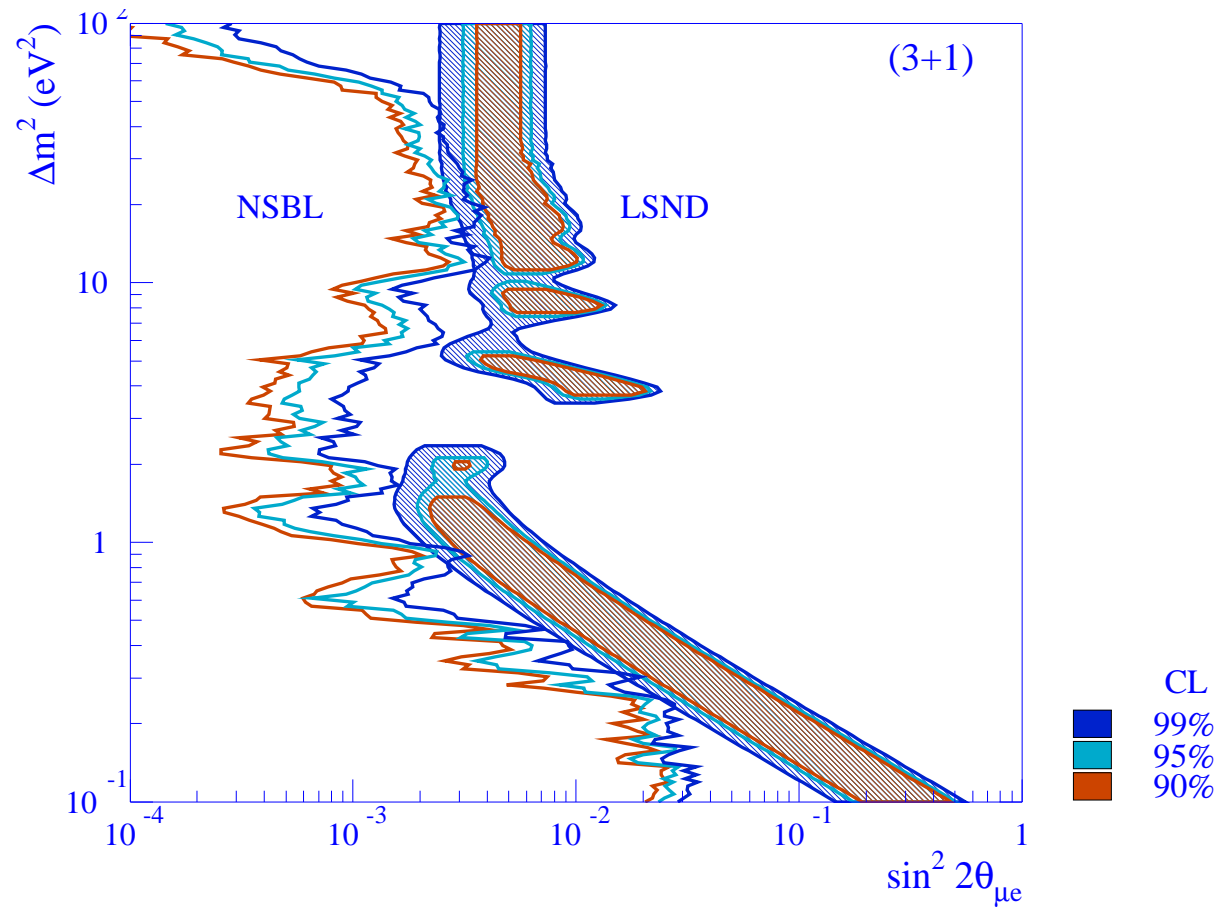$$P(\bar\nu_\mu \to \bar\nu_e) = 4U^2_{e4}U^2_{\mu4}\sin^2(1.27\Delta m^2_{41}L/E)$$

- Two-neutrino approximation is satisfied $\Rightarrow$ define:

$$\Delta m^2 \equiv \Delta m^2_{41}, \qquad \sin^2 2\theta_{\mu e} \equiv 4U^2_{e4}U^2_{\mu4}$$

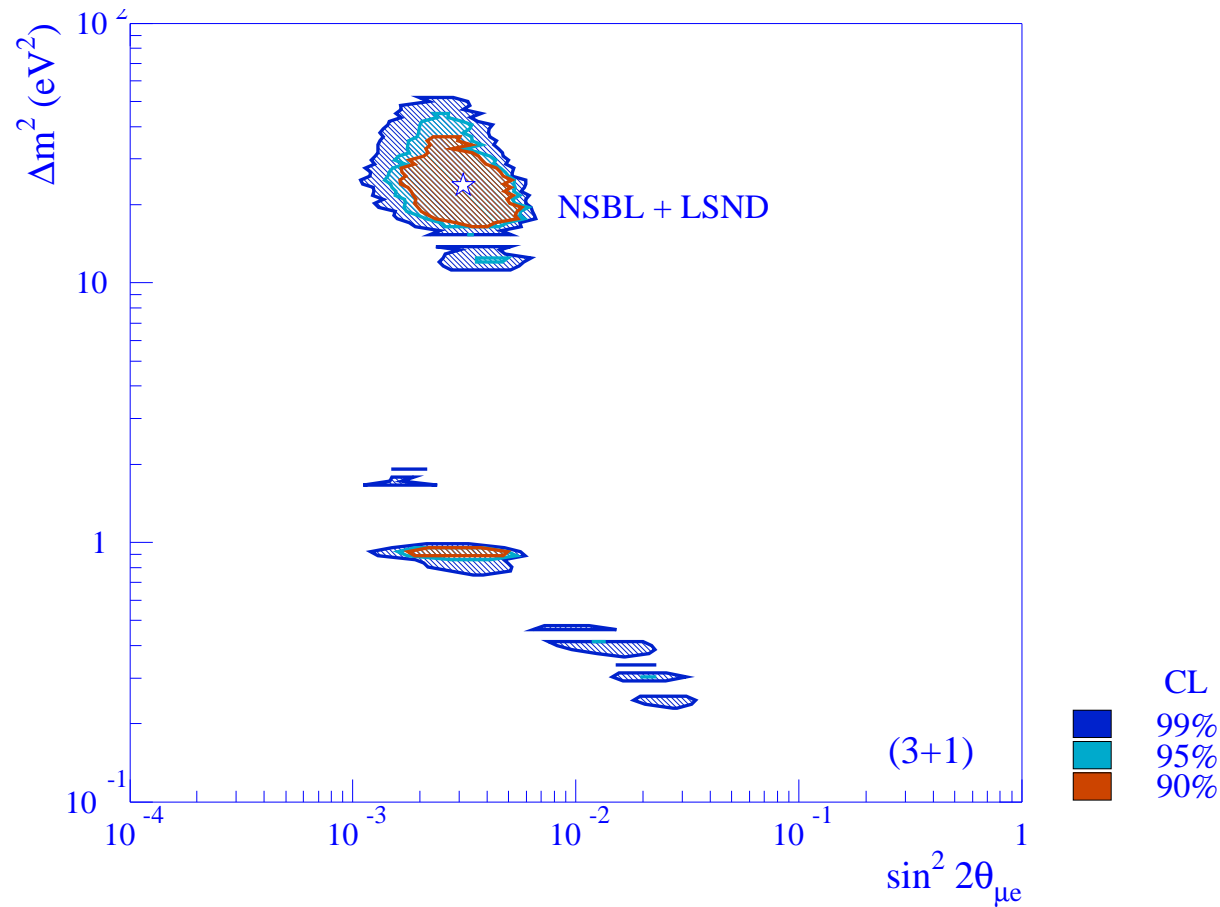# Treat NSBL and LSND data sets separately
(3+1) case

- NSBL and LSND data sets are only marginally consistent with each other
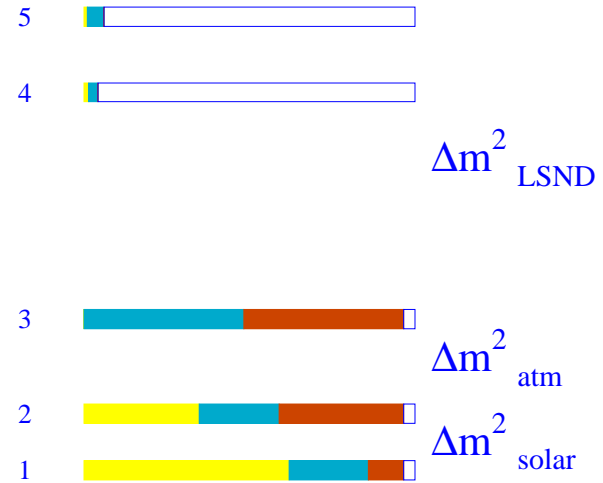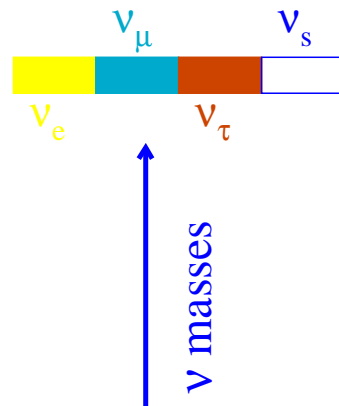
Combine NSBL and LSND data sets
(3+1) case

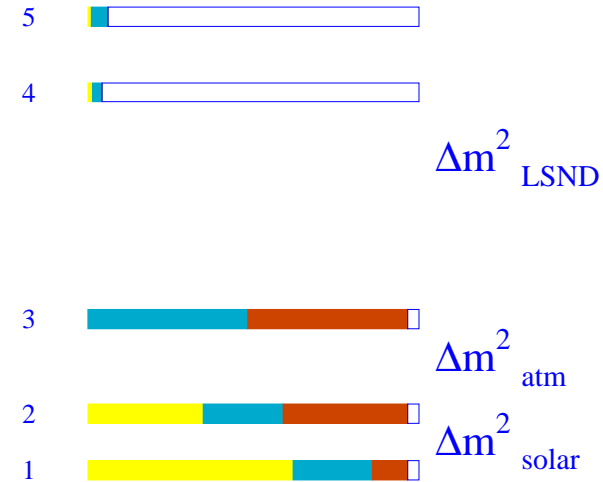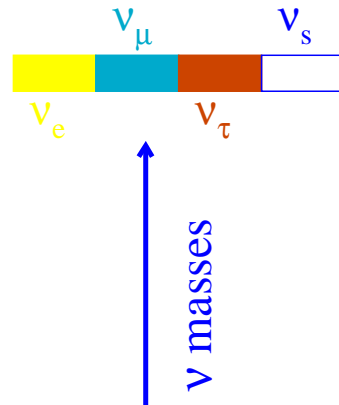● Assuming statistical compatibility of all SBL results, a joint analysis gives:

● Best-fit: $\Delta m^2 = 23.8\ eV^2$, $U_{e4} = 0.13$, $U_{\mu 4} = 0.22$

(3+2) models and SBL experiments

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- Six parameters probed: Δm^2_{41}, U_{e4}, $U_{\mu4}$, Δm^2_{51}, U_{e5}, $U_{\mu5}$

- More than one Δm^2 contributes to the oscillation probability:

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = 4(U_{e4}U_{\mu4} + U_{e5}U_{\mu5})(U_{e4}U_{\mu4}\sin^2 x_{41} + U_{e5}U_{\mu5}\sin^2 x_{51}) - 4U_{e4}U_{\mu4}U_{e5}U_{\mu5}\sin^2 x_{54}$$

$$x_{ji} \equiv 1.27\Delta m^2_{ji}L/E$$

- Use NSBL data to derive the upper limits on the $\bar{\nu}_\mu \to \bar{\nu}_e$ probability averaged over the LSND L/E distribution:

$$p_{LSND} \equiv \langle P(\bar{\nu}_\mu \to \bar{\nu}_e)\rangle_{LSND}$$

Compare (3+2) and (3+1) models

● Allowed values for the LSND oscillation probability (δ = confidence level value):
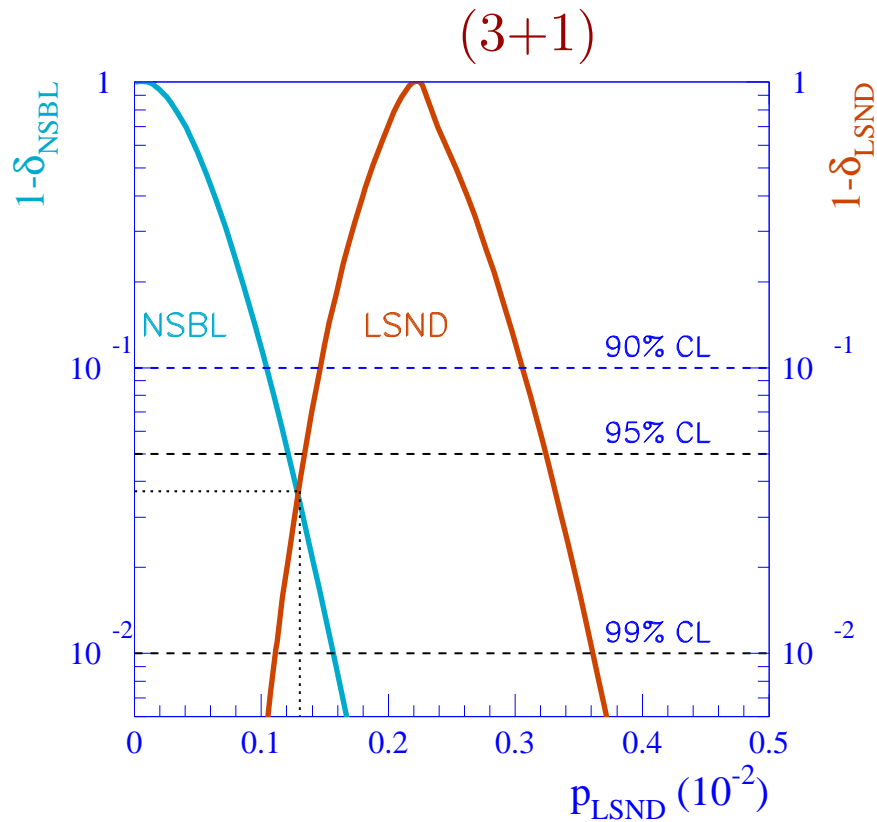
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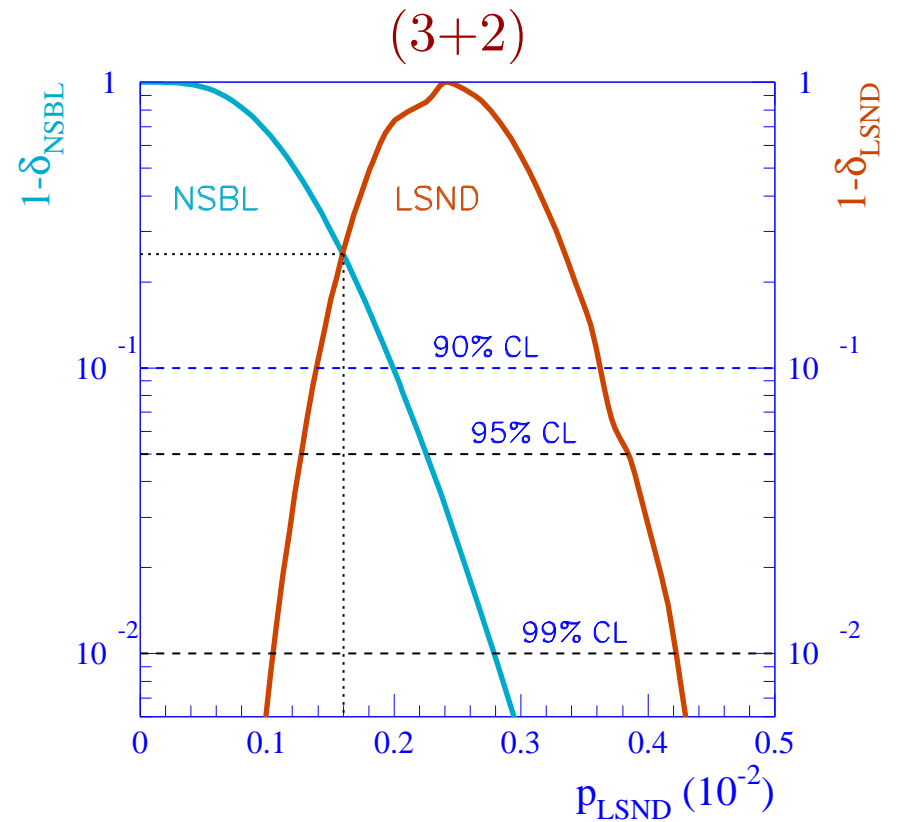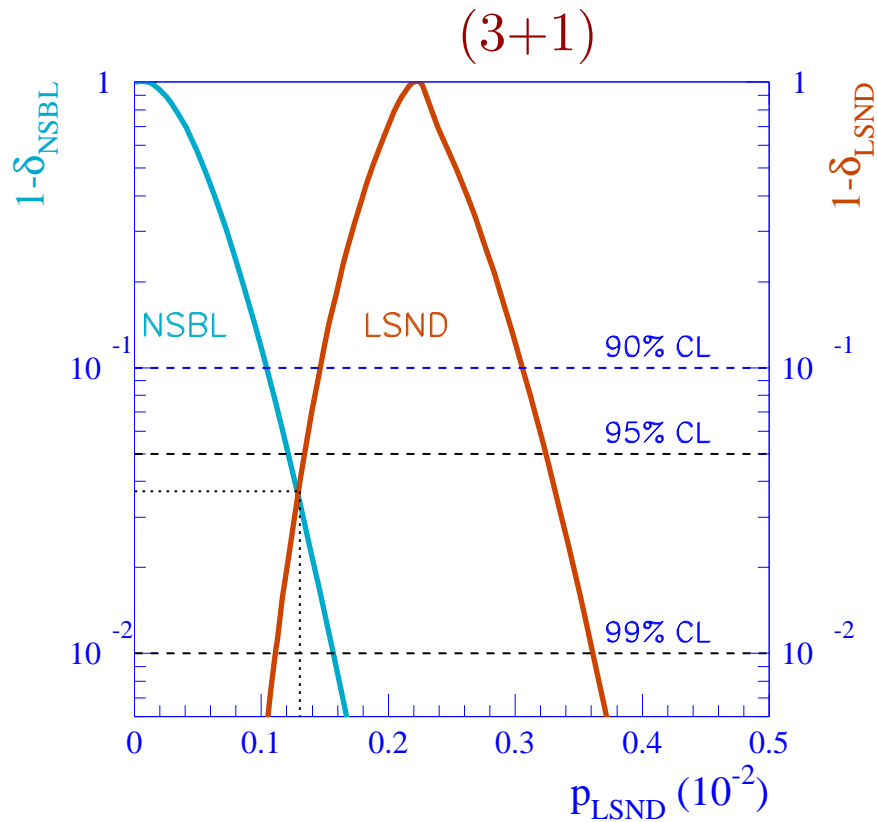
- Two sterile neutrino models fit SBL data significantly better

Combine NSBL and LSND data sets
(3+2) case

- $(\Delta m_{41}^2, \Delta m_{51}^2)$ allowed region from joint NSBL+LSND analysis:
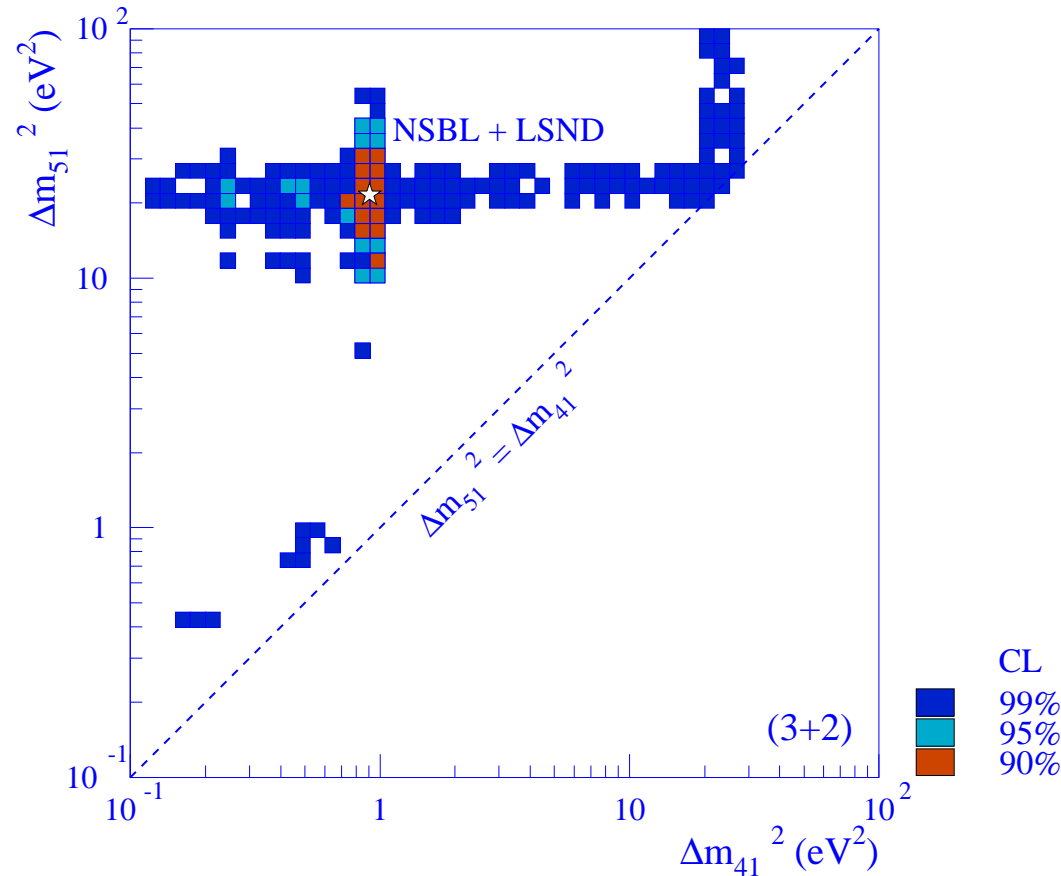
- Best-fit:

  $\Delta m_{41}^2 = 0.91 \ eV^2, \ U_{e4} = 0.12, \ U_{\mu 4} = 0.17, \ \Delta m_{51}^2 = 21.5 \ eV^2, \ U_{e5} = 0.07, \ U_{\mu 5} = 0.22$

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(3+2) case

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Is this in contradiction with cosmology?
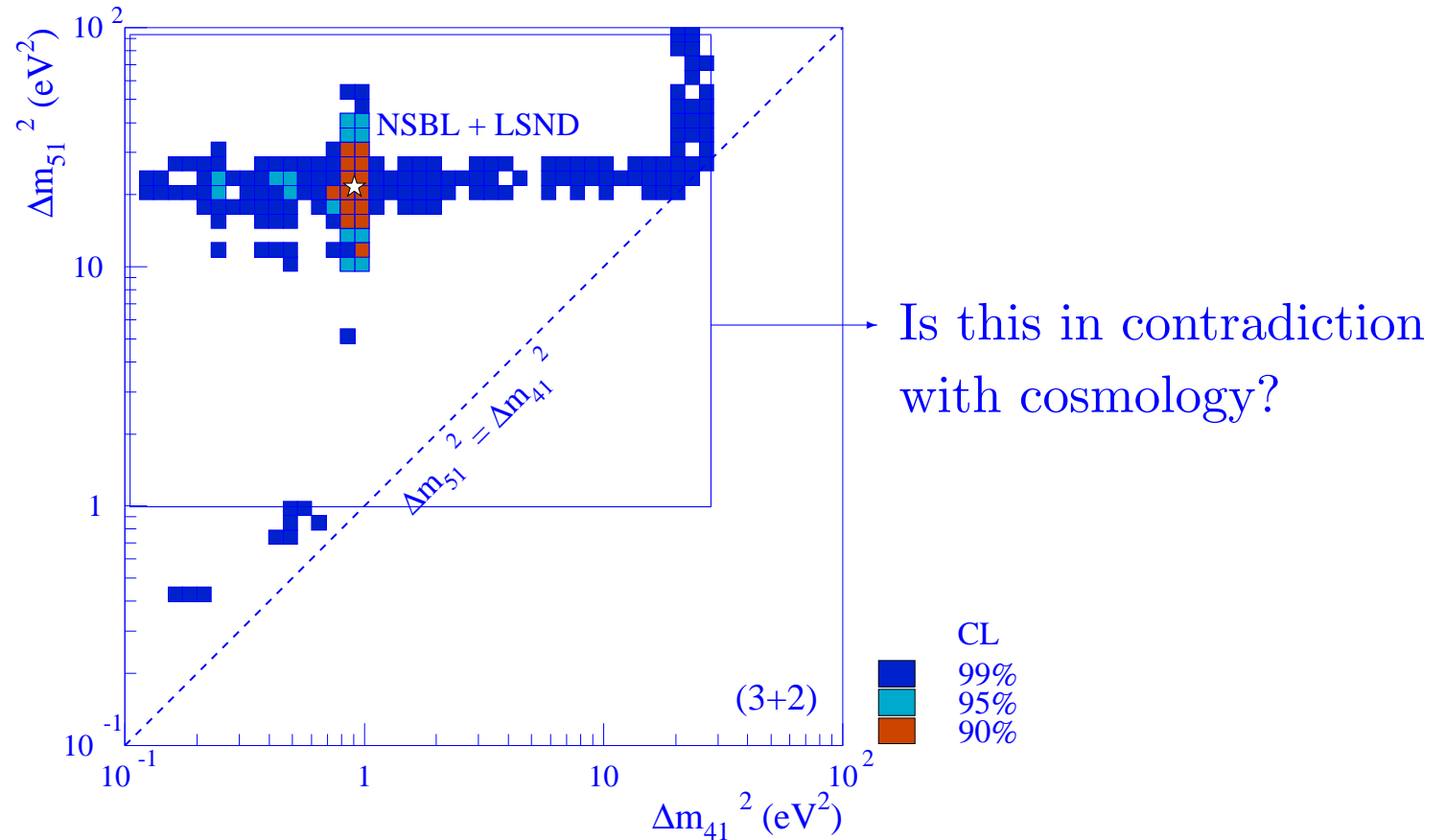
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Cosmology and massive neutrinos

- Standard cosmology (ΛCDM) assumes three active, massless, neutrinos, and no lepton asymmetry

- Observations $\sim$ agree with predictions of standard cosmology:

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Example: primordial He/H ratio Y_p as a function of the baryon-to-photon ratio
(Di Bari, `astro-ph/0302433`)
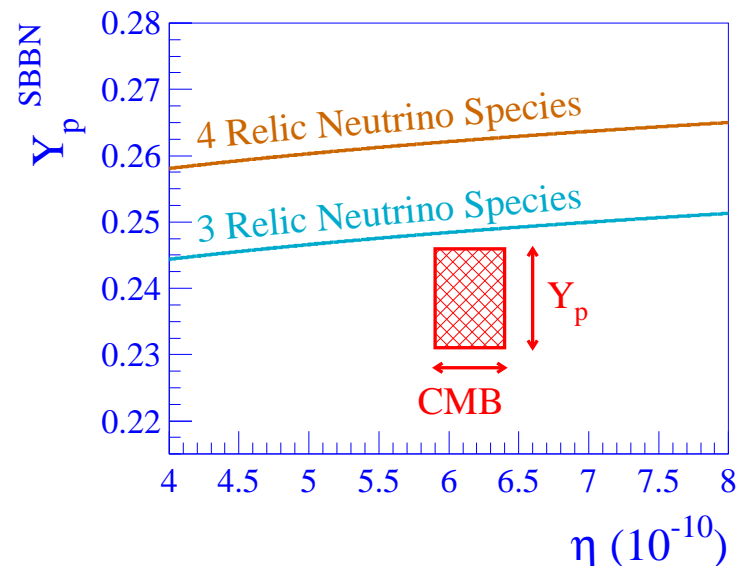
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  (for a review, see: Abazajian, `astro-h/0205238`)

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- Cosmological constraints on sterile neutrinos should be taken with caution, and in any case complemented with terrestrial experiments (where the interpretation of data is easier)

Future sterile neutrino searches at high Δm^2

- The unitarity of the mixing matrix means that $\sim$ all of the mixing parameters measurements constrain active-sterile mixing, at least indirectly:

  - Improve limits on $(\nu_e \longrightarrow \nu_s)/(\nu_e \longrightarrow \nu_{\mu,\tau})$ at $\Delta m^2_{\text{solar}}$
    (Example: next-generation, real-time pp solar neutrino experiments)

  - Improve limits on $(\nu_\mu \longrightarrow \nu_s)/(\nu_\mu \longrightarrow \nu_\tau)$ at Δm^2_{atm} with LBL accelerator experiments (see: H. Gallagher, "MINOS Experiment Update", this session)

  - Improve reactor limits on $\nu_e \longrightarrow \nu_x$ over a wide Δm^2 range
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- Direct searches at high Δm^2:

  - Test $\nu_\mu \longrightarrow \nu_e$ signal at Δm^2_{LSND}: MiniBooNE

  - Improve limits on $\nu_\mu \longrightarrow \nu_s$, $\nu_\mu \longrightarrow \nu_\tau$ at Δm^2_{LSND} with SBL accelerator experiments
    (Example: $\nu_\mu \longrightarrow \nu_x$ sensitivity for FINeSE+MiniBooNE)

  - Δm^2_{LSND} range is not known precisely $\Rightarrow$ several SBL experiments help

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- Combining LSND with other oscillation results provides hints where to look

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- If LSND is confirmed, additional $\nu_\mu \longrightarrow (\nu_e,\ \nu_\mu,\ \nu_\tau)$ measurements at SBL are very important to disentangle the neutrino mass and mixing pattern

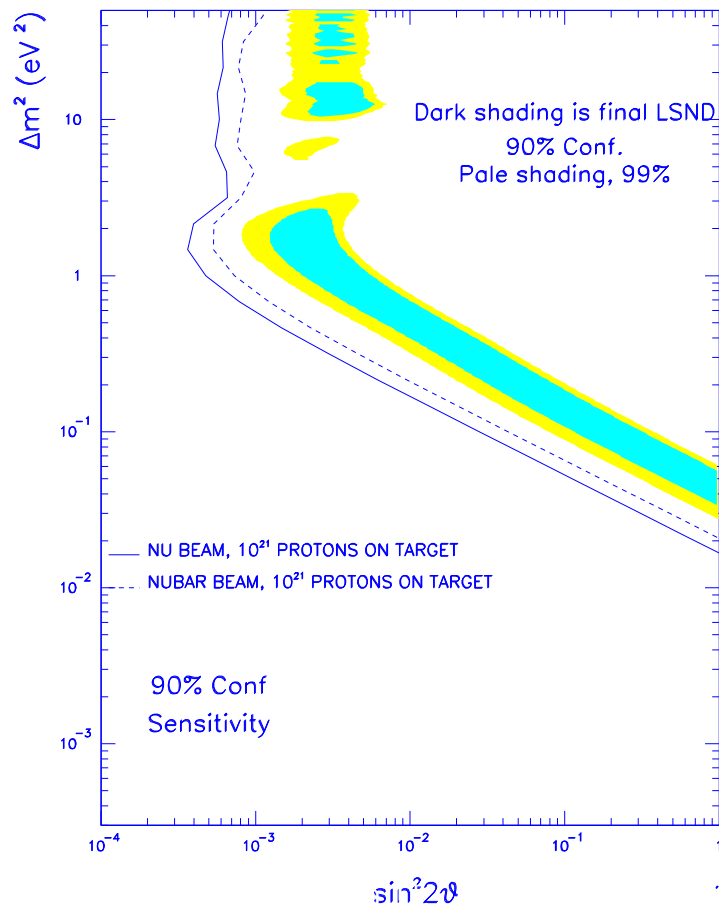# $\bar{\nu}_e$ disappearance sensitivity of future reactor experiments

Plot from: J. Link, "The future of Neutrino Experiments at Nuclear Reactors", ACCF, Thursday session (go back)
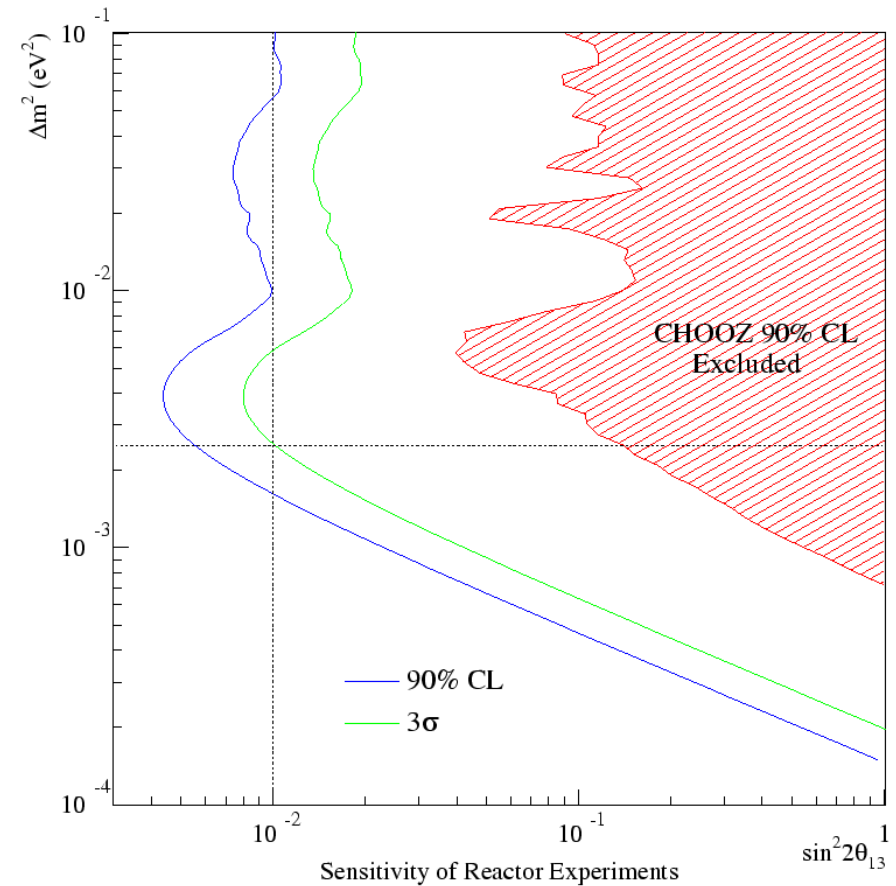
- See also: K. M. Heeger, "Reactor Neutrino Measurements of θ_{13}", NEU, this session

# $\nu_\mu \rightarrow \nu_e$ appearance sensitivity in MiniBooNE

- T. L. Hart, "Neutrino Oscillation Search at MiniBooNE", NEU, Tuesday session

- MiniBooNE will address in a definite and independent way the LSND evidence for $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ oscillations

Dark shading is final LSND
90% Conf.
Pale shading, 99%

NU BEAM, 10²¹ PROTONS ON TARGET
NUBAR BEAM, 10²¹ PROTONS ON TARGET

90% Conf
Sensitivity

Δm^2 (eV²)

$\sin^2 2\vartheta$

- definite: same L_ν/E_ν ratio as for LSND and enough statistics to cover the LSND region at the 5σ level

- independent: $E_\nu = 0.3 - 1.5$ GeV and $L_\nu = 540$ m are both a factor of 10 larger than LSND, resulting in very different backgrounds to the oscillation search and systematics for the neutrino flux and particle ID (go back)

ν_e disappearance sensitivity with MiniBooNE + FINeSE

Plot from: B. T. Fleming, J. Monroe
(go back)
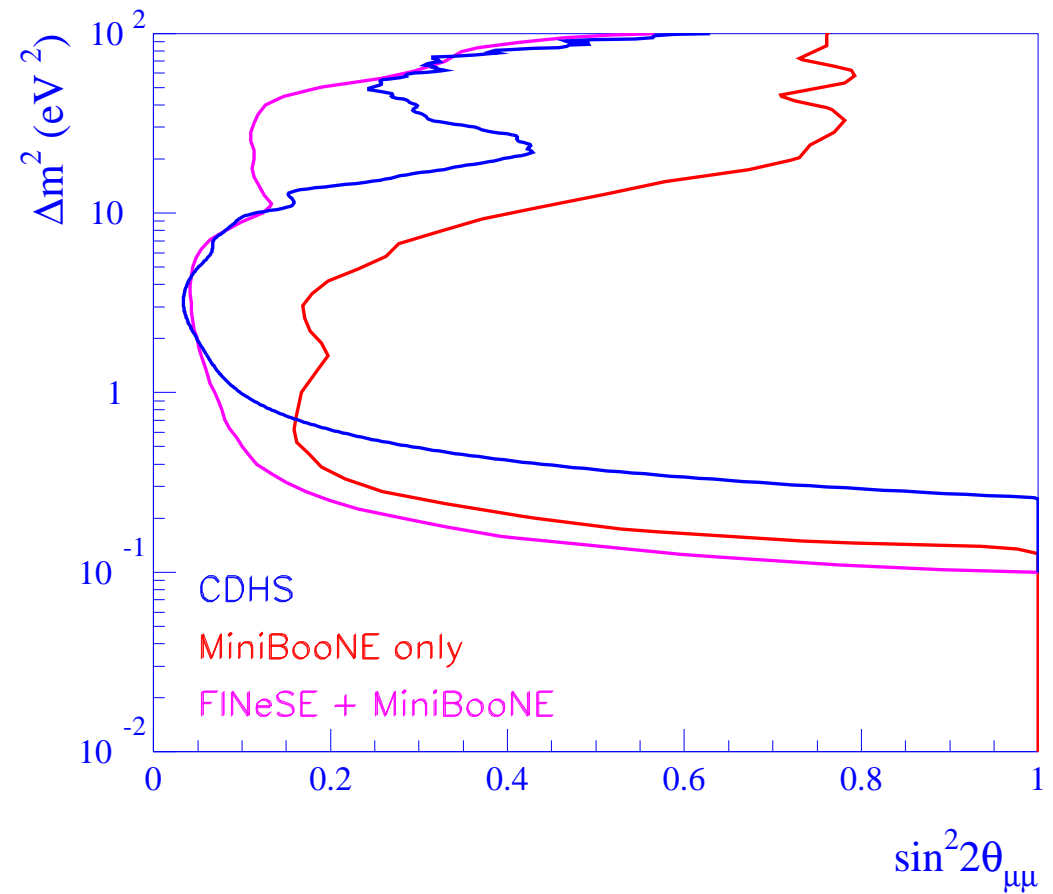
- M. O. Wascko, "Neutrino Physics at FINeSE", NEU, this session